Steel-Based Tail Actuators for Micro-Air-Vehicles

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Abstract—**This work presents an animation of the sporangial motion for making bionic tail flaps of micro-air-vehicles (MAVs) regarding energy saving. A SUS-304 steel foil of 40 μm-thick is used as the substrate and Nd-YAG laser cutting is performed to construct the surface tension-driven actuator. Surface modification including parylene coating and oxygen plasma treatment are tried to enlarge the actuation stroke angle.**

Keywords- steel foil; tail actuator; laser cutting; micro-air-vehicles (MAVs)

I. INTRODUCTION

Several works about the biomimetic flapping micro-air-vehicles (MAVs) of Fig. 1(a-b) have ever been reported [1-3]. These MAVs of 20 cm-span and 10 gram-weight can continuously fly for minutes with power consumption of 1-2 W only. However, the flight endurance is decreased dramatically if more flight control actuations for direction change are exercised. That is because the conventional tail actuators are the electro-magnetic solenoids exhausting most of MAVs' battery power. It might save much energy by mimicking the comb structures of fern plants as they release their spores during the period of dry season. The prior art of ref. [4] used PDMS as the comb material for actuation and another previous work of ref. [5] selected the high aspect-ratio SU-8 resist to replace PDMS. However, both cases of using PDMS and SU-8 with several tens of μm thickness have the common problem of small actuation force so that they could hardly push any mm-size mechanism with obvious actuation stroke.

II. FABRICATION AND TESTING

A. Material Selection and Tail Operation

The SUS-304 stainless steel foil of 40 μm-thick has larger Young's modulus and yield strength than the previous polymers like PDMS and SU-8. (Herein the authors regard the beam stiffness as the product of Young's modulus and moment of inertia [6]. With the fixed moment of inertia, stiffness depends on Young's modulus.) Accordingly the authors asked a foundry service of a Nd-YAG laser cutting (355 nm UV) to follow the comb-shape contour path shown in Fig. 1(c) for 15 times with the scan speed of 400 μm/s on the steel foil, and therefore obtained many bionic comb actuating units. (http://www.micron-laser.com) The minimum line width of the laser cutting is 50 μm. Each actuating unit has 50 pitches of comb fingers, and many identical units of them

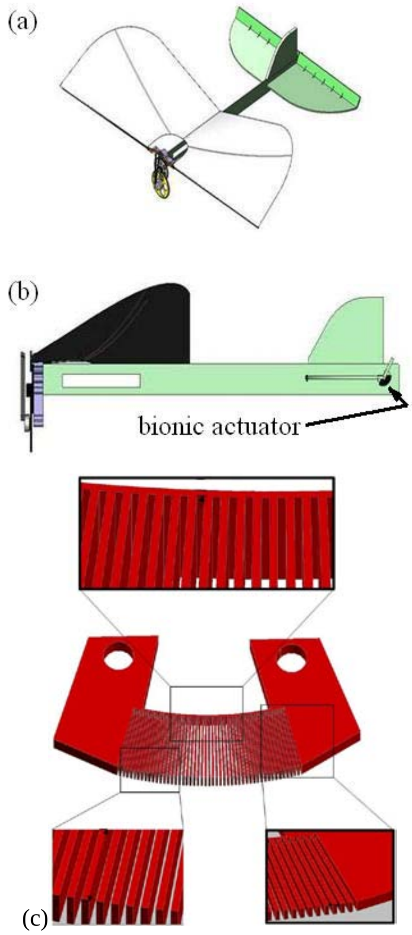

Fig. 1. (a) Flapping micro-air-vehicles (MAVs); (b) Bionic actuators as the control surfaces for MAVs; (c) The comb structure of the bionic actuator

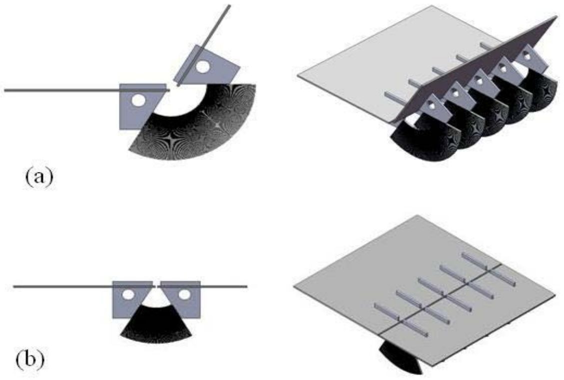

Fig. 2. Working principle of the comb-shaped bionic actuator. (a) Flap up without liquid nor surface tension (dry case); (b) Flap flat with liquid and surface tension (wet case).

could be assembled into one MAV control surface to provide the necessary force for flight control. The working situations demonstrated in Fig. 2 is the depletion-mode operation of the bionic actuator. In other words, the bionic actuator is designed to always fill with water (the water reservoir and the filling channel have not shown yet), and its surface tension keeps the control flap parallel to the air stream, as in Fig. 2(b). When a yawing turn or a pull-up maneuver is necessary during the flight, a current impulse will be fed into the steel actuator to evaporate the water absorbed in the comb structure. So the actuator restores to its original shape and the flap bends up or toward to lateral direction as shown in Fig. 2(a).

B. Formula for the Actuation Stroke Angle

The spreading angle or the stroke angle change $\Delta\psi$ due to the water capillary force the comb-shaped bionic actuator is linearly modeled as follows [5].

$$\Delta\psi = \frac{12\gamma_{la} NR(R+H)w}{EHb^3} \qquad (1)$$

where γ_{la} is water surface tension (γ_{la}=0.073 N/m); N is the number (N=50) of the comb-shaped beams; R is the length (R=3000 μm) of the comb; H is the depth (H=40 μm) of the multi comb structure; w is the root gap between two comb beams (w=50 μm); E is the Young's modulus (E=200 GPa) of the steel comb; b is the root width (b=50 μm) of the comb beams. With the above dimension, the actuation area of the comb-shaped cantilevers can be confined within 5 mm.

By (1), one can estimate the actuation stroke angle change $\Delta\psi$ as 1.14°. Even though this angle change is small and far less than the ordinary 5-15° for (micro) air vehicles, at least it fits the small deformation assumption of the elasticity theory applied to deriving (1) in ref. [5].

C. Testing without Surface Modification

Fig. 3 shows the comb angle change of the steel-based actuators subject to water surface tension. These actuators are just brought from the laser cutting process and have no other treatment. From Fig. 3(a-b), the actuating comb only has a rotating stroke of 3° (from 38° to 35°). Compared to the previous estimated value of 1.14°, there still exists great error between the theoretical and the experimental data. Two arguments may be responsible for clarifying the reasons why. First, the mechanical property (e.g., the Young's modulus E) of the steel after the laser cutting may change a lot. Second, the authors found the steel surface a hydrophobic one (which contact angle is 105.5° shown in Table I) after the laser cutting. So the water is hard to fill into the gaps among the comb structure. Therefore a surface modification of coating parylene on the steel surface is performed in the next step to verify the above arguments.

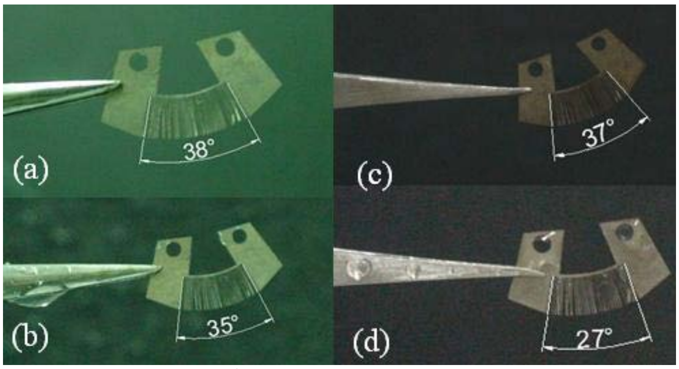

Fig. 3. Angle changing of the steel-based bionic actuator due to the water surface tension: (a) steel actuator without water; (b)steel actuator with water; (c) parylene-coated actuator without water; (d) parylene-coated actuator with water.

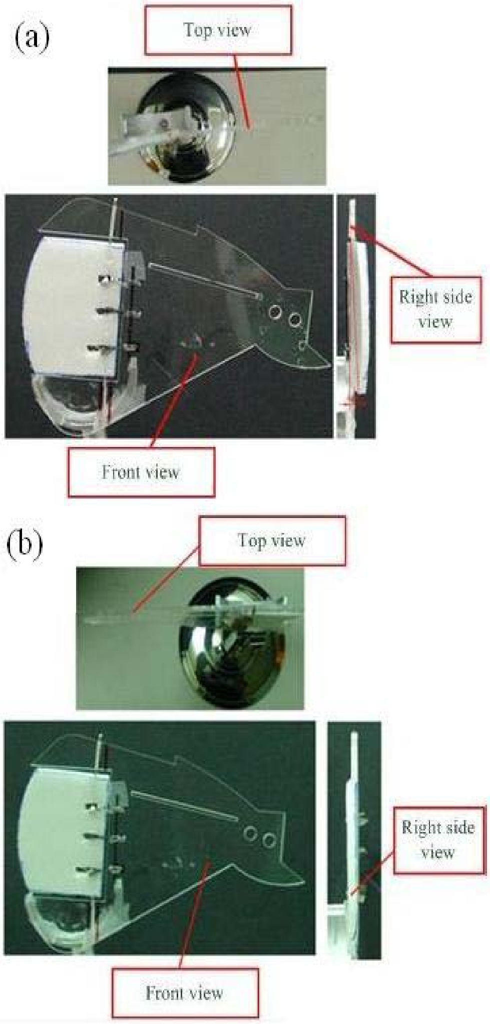

Fig. 4. The assembly and testing of the actuator on the MAV's stabilizer: (a)no water; (b)with water.

D. Testing with Parylene Coating

After being coated with a parylene film around, the contact angle (and the surface roughness) of bionic actuator units in Table I is shown to be a hydrophilic case of 68.7°. At the first glance, the 50 μm gap between two comb fingers seems to be decreased to 30 μm by adjusting the parylene thickness as 10 μm similar to the gap-filling of ref. [7]. Parylene coating effectively enlarged the actuation force and the corresponding stroke angle up to 10° (from 37° to 27°) in Fig. 3(c-d). The authors also tested the surface modification of oxygen plasma on the device. The surface is more hydrophilic but the actuation stroke is almost the same as the one without plasma treating.

Moreover, the authors check the formula of (1) and see that the dimensions of w, b and H are directly related with the elastic deformation of the bionic actuator. Even the steel is coated with parylene now, but the steel material has a much larger Young’s modulus than parylene and still dominates the deformation behavior. So the values of w, b and H used in the refined calculation of the actuation stroke angle of the device by (1) are assumed to have no change. (On the other hands, R and H in the numerator of (1) change a little bit.) In other words, the stroke angle of 10° in this case might be explained by a new Young’s modulus (23.2 GPa) of the laser-machined steel foil under the assumption that 100% water enters into the gap of the comb exactly. With the new value of Young’s modulus after the laser cutting, the authors can also calculate reversely that only 30.3 % of the gap has been filled with water in the previous case without parylene.

E. Actuation Testing after the Tail Assembly

Figure 4 shows the assembly and testing of the bionic actuator installed on the MAV’s vertical stabilizer. The effective stroke angle again decreases to 4° due to the large mass loading of the vertical stabilizer. Adding more bionic actuation units into the MAV’s tail and making some modification on the assembly procedure are still necessary in the future.

III. CONCLUSION

Steel-based bionic actuators using water surface tension was proposed and preliminarily investigated in this paper. The actuation area of the comb-shaped cantilevers is confined within 5 mm, and the maximum actuating angle change is tested as 10° after the device was coated with parylene film. The Nd-YAG laser cutting is convenient to the machining of the bionic actuator, but it might imply a degradation issue of the steel sheet after the laser processing. The first try of the actuator to the vertical stabilizer of a flapping MAV has been done, and the low power consumption as well as the array-configuration for this bionic actuator is highly expected.

ACKNOWLEDGMENT

This work was partially supported by the National Science Council of Taiwan with the project no. of NSC-101-2-E-032-001-MY3. The authors also thank the travel support from Tamkang University.

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TABLE I. DATA OF SURFACE ROUGHNESS AND CONTACT ANGLES FOR THE BIONIC ACTUATING UNITS: (THE SURFACE ROUGHNESS WAS MEASURED BY KLA-TENCOR ALPHASTEP-500; CONTACT ANGLES ARE MEASURED BY FIRST TEN ANGSTROMS-125; EACH DATUM IS AVERAGED FROM 3 SAMPLES AND 3 LOCATIONS FOR EACH SAMPLE AT LEAST.)

	Steel		Steel coated with parylene	
	Before laser cutting	After laser cutting	No oxygen plasma treating	With oxygen plasma treating
Surface roughness (angstrom)	473	1405	541	832
Contact angle (degree)	60.5°	105.5°	68.7°	21.9°